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Challenges in a Freshman General Education Class

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Integrating the IDEO Design Process to Find Solutions to Engineering Challenges in a Freshman General Education Class

Introduction

How undergraduates are introduced to the discipline of engineering at the college level can have long-term educational and professional implications, including influencing decisions to pursue or leave engineering majors and validating beliefs about the purpose of engineering in society [1]. Classroom lectures have been traditionally used within introductory engineering courses as they can transmit large amounts of content [2]. However, they are generally less effective in helping undergraduates engage with and apply content [3]. In recognition of this, learner-centered approaches are increasingly being used in introductory engineering classes [4].

Learner-centered approaches are based in constructivist learning theories, one of which is Design-Based Learning (DBL). DBL posits that in problem solving situations, learners draw on their own past experiences and pre-existing knowledge to discover phenomena and how those phenomena are related, and what is desirable to learn next [5]. Learners interact with their environment through exploration, object manipulation, contemplation of questions and controversies, and experimentation. DBL activities promote learner-centered discovery as opposed to teacher-centered methods [6] and focus on planning, constructing, evaluating, and iterating a particular device, process, or solution to authentic problems [7], [8]. One DBL approach used to specify and teach problem-solving processes in science and mathematics is the engineering design process.

In this study, we describe the use of a modified version of the engineering design process within a large introductory engineering course offered in fall of 2019 at our midsize urban research university. The previous course format and delivery were largely teacher-centered. Thus, our motivation to integrate a modified design process into the course was to forefront learning-centered discovery, which is linked to increased learning, engagement, and retention of STEM-aspirational students [4], [9]. Our revised version of this course highlighted the pressing need for students to recognize how engineering can respond to society's challenges (as outlined by the National Academy of Engineering Grand Challenges for Engineering).

The design process was first made popular by IDEO, a design firm originating at Stanford University [10]. IDEO's design process is a human-centered method for developing breakthrough ideas using multidisciplinary teams and building and testing prototypes [11]. The process involves four main steps: (1) Introduction/inspiration, (2) Synthesis, (3) Ideation/experimentation, and (4) Implementation [12]. The introduction/inspiration stage involves going out into the world and observing, shadowing, interviewing, and interacting with people in various fields, thereby proactively seeking experiences to inspire human-centered innovation. The synthesis stage involves making sense of information learned during the inspiration stage through recognizing patterns, identifying themes, and finding meaning. In this stage, what was learned is translated into "actionable frameworks and principles" [12]. In the ideation/experimentation stage, ideas and prototypes are rapidly generated and explored until workable solutions are found. In the implementation stage, the design is redefined and prepared for public presentation.

Our review of recent literature indicates that the design process is increasingly used at universities across the globe. For example, the design process is woven throughout graduate information management courses at the University of St. Galen in Switzerland [13]. It underpins

MIT's D-Lab course, Developing World Prosthetics, dedicated to creating low-cost prosthetic and assistive devices [14]. It is an integral component of the recently implemented development engineering doctoral courses at UC-Berkeley [15]. Finally, the capstone course of the software engineering program at Lappeenranta University in Finland incorporates the design process structure [16]. In all cases, use of the design process has resulted in increased student engagement. However, a closer look at these examples and others suggests that the design process is most commonly found in advanced undergraduate or graduate courses with a small enrollment. Given this, we wondered to what extent the design process is transferable to introductory courses that enroll close to two hundred students, most of whom are in their first year in college. Arguably, these are the students who might most benefit from design process participation.

Our decision to use a modified design process in a large, introductory engineering course was informed by two conceptual contexts, disciplinary expertise development and academic integration. In terms of expertise development, freshmen students often encounter introductory courses in which disciplinary knowledge is not clearly organized and/or is presented in a way in which its meaningful application is unclear [17]. However, the IDEO process incorporates pedagogical activities that strengthen disciplinary expertise development, such as learning how to create and structure knowledge, discern meaningful patterns, and grapple with ambiguity [18], [19]. In terms of academic integration, it is well established that large introductory courses rarely contribute to freshmen students' sense of belonging on a college campus [17]. Academic integration is, however, linked to increased student interactions with peers and course instructors [20]. Thus, our use of the design process intentionally served the purpose of academically integrating students both into their campus environment and, more broadly, the engineering discipline. In the following section, we describe how we used the design process in our course.

Course Learning Outcomes, Participants, and Site

The course "Engineering in Society" is a single-semester course that meets for 50-minute sessions three times per week. There are no course prerequisites. The redesigned fall 2019 student learning outcomes for the course were to: (1) Gain awareness of the National Academy of Engineering Grand Challenges for Engineering, (2) Demonstrate an understanding of engineering ethics, (3) Apply the design process to a National Academy of Engineering Grand Challenge, and (4) Develop/strengthen collaborative skills and abilities as part of a design team.

Enrollment in large, introductory courses often fluctuates early in the semester. One-hundred and ninety-six students were enrolled at the start of the course. Six withdrew in the first week; three remained enrolled but completed only initial assignments or none at all. Table 1 displays enrollment demographics of the 187 (95%) students who were retained and engaged in the design process. While the current COVID-19 situation makes it difficult for us to obtain retention statistics from previous offerings of this course for comparison, we believe the retention percentage of 95% likely represents a significant improvement.

Table 1: Enrollment Demographics of Course

Fall 2019	
All Students Participating in Design Process	187
School of Engineering	136
School of Medicine (pre-med program)	17
College of Arts and Sciences	11
School of Management	8
School of Biology/Chemistry	6
School of Pharmacy (pre-pharmacy)	2
School of Dentistry (pre-dentistry)	1
School of Education	1
Undecided/No Response	5
Female	60
Male	127
Freshmen students	167
Transfer students	20

We measured three constructs in the students at the beginning of the course: problem solving confidence, growth mindset, and engineering identity. Problem solving confidence was measured using the Problem Solving Confidence subscale of the Problem Solving Inventory [21]. In the current study, an exploratory factor analysis (EFA) using principle axis factoring (PAF) and Promax rotation was performed, which resulted in a single factor solution explaining 31% of the variance in the items. Cronbach's alpha reliability was .80.

Growth mindset was measured using items from [22] forming three composite scales: Beliefs About Intelligence, Learning Goal Orientation, and Negative Beliefs About Effort. An EFA using PAF and Promax rotation was performed on each scale, and each resolved in a single factor solution explaining between 46% and 53% of the variance in the items. Cronbach's alpha reliability coefficients were also estimated for each scale: Beliefs About Intelligence, .87; Learning Goal Orientation, .71; and Negative Beliefs About Effort, .82.

Engineering identity was measured with the engineering identity scales of the Identity and Persistence in Engineering survey [23]: Performance/Competence, Interest, Engineering Identity, and Recognition by Others. [24] found strong evidence of a four factor structure for the scales, which was replicated in this study using PAF with Promax rotation. The results were a four-factor solution explaining 70% of the variance in the items, factor loadings ranging from 0.56 to 0.91, and factor correlations ranging from .37 to .70. The four subscales had Cronbach's alpha reliability coefficients ranging from .82 to .93.

In most ways, the students were no different than sophomores, juniors, and seniors we measured in a separate study. However, some of their measures were significantly lower than the upperclassmen, including: problem-solving confidence (one-way ANOVA using class as a four-level factor: $F[3, 304] = 2.76$, $p = .04$); engineering performance/competence ($F[3, 304] = 5.59$,

$p < .001$); and recognition by others as an engineer ($F[3, 304] = 12.47$, $p < .001$). These differences can probably be explained by differing levels of experience among the classes in the engineering curriculum. Unfortunately, while post-surveys were administered for all three constructs, due to technical difficulties, they did not yield usable data.

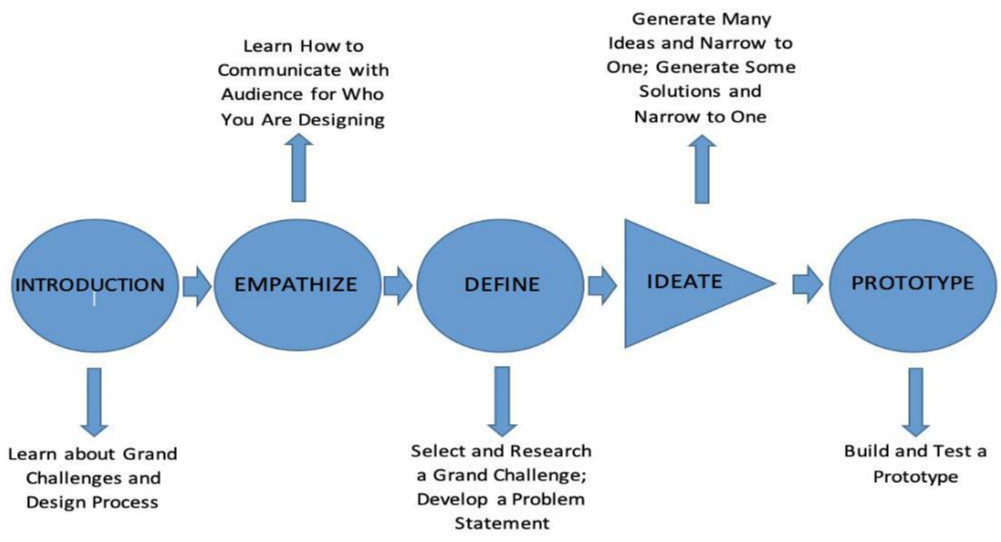
The course was taught by one lead and one support instructor. The lead instructor, a faculty member in the School of Engineering, presented all course material, created course assignments, and participated in grading assignments. The lead instructor had previous experience teaching the design process in advanced undergraduate courses enrolling approximately 20 students. The support instructor, a faculty member in the School of Engineering, attended all course sessions and participated in grading assignments. The support instructor had no background in teaching the design process, and in general, limited background using student-centered pedagogical approaches. A faculty member from the School of Education, who did not present or evaluate any student-generated material, attended approximately half of the course sessions to learn about the design process and observe design teams at work.

The university at which our course was offered is located in the heart of a large metropolitan area. It serves approximately 16,000 students, 1,700 of whom are students within the School of Engineering. The university has struggled with student engagement and, relatedly, student retention; a recent institutional analysis of retention rates revealed that one-third of STEM aspirational students leave the university within their first two years. As a result, it has begun to explore and implement engagement and retention strategies. A heightened focus on using learner-centered pedagogies (e.g., the design process) to engage and retain students has become somewhat more common on the campus (but is by no means ubiquitous).

Applying the Design Process in a Large Introductory Course

Course curriculum was structured around five modules representing a modified version of the IDEO process: (1) Introduction, (2) Empathize, (3) Define, (4) Ideate, and (5) Prototype. Figure 1 provides a visual of the design process we used in our course.

Figure 1. Design Process Used in Course



In each module, students submitted a written response to describe what they had learned; each reflection assignment was worth five percent of the overall grade. In addition, students were required to individually upload onto the online course learning platform a series of assignments to document their team's progress. These assignments constituted the remaining percentage of the overall grade.

In the *Introduction* module, students first learned about the National Academy of Engineering Grand Challenges for Engineering. As part of discussion groups, they were asked to prioritize the challenges and identify those that most interested them. Most students were previously unaware of these challenges. In reflecting what was learned in this module, one student stated:

> I learned the responsibility of engineering. With all the rewarding aspects of engineering comes responsibility. The grand challenges emphasized the responsibility engineers have to society. If engineers have the tools to create, they should use them to create good. This is important to acknowledge so that engineering can remain ethical and just.

Students were then introduced to the design process by viewing videos showcasing it, such as one in which a wheelchair was designed to be used in rough terrain often encountered by those in underdeveloped countries. The videos appeared to broaden students' understanding of engineering. As one student offered in her written reflections of what she learned in this module:

> I learned how engineering can greatly impact someone's life. In the video about the bike helmet and the wheelchair, I saw the societal impact of engineering. In the case of the helmet, engineers can save lives, and the wheelchair greatly improved the quality of life for its users. These videos made me understand the purpose and reward of engineering.

As a warm-up activity for more involved design process engagement later in the semester, students met in a large auditorium and formed teams that ranged in size from three to seven students. Each team was given recycled cardboard boxes, newspaper, scissors or box cutters, and a roll of duct tape. Each team then responded to the design prompt, "Within 50 minutes and using the materials your team was given, design a full-sized chair that can hold the weight of a person. You should develop the design criteria and constraints as a group – what do you think is important in designing your chair?" Teams documented their ideas, challenges, proposed solutions, and selected solution; they then built a prototype. Figure 2 depicts a team's thought process toward solution generation, while Figure 3 depicts the chair the team designed in response to this prompt.

Figure 2. Example of a Team's Thought Process Underlying Chair Construction

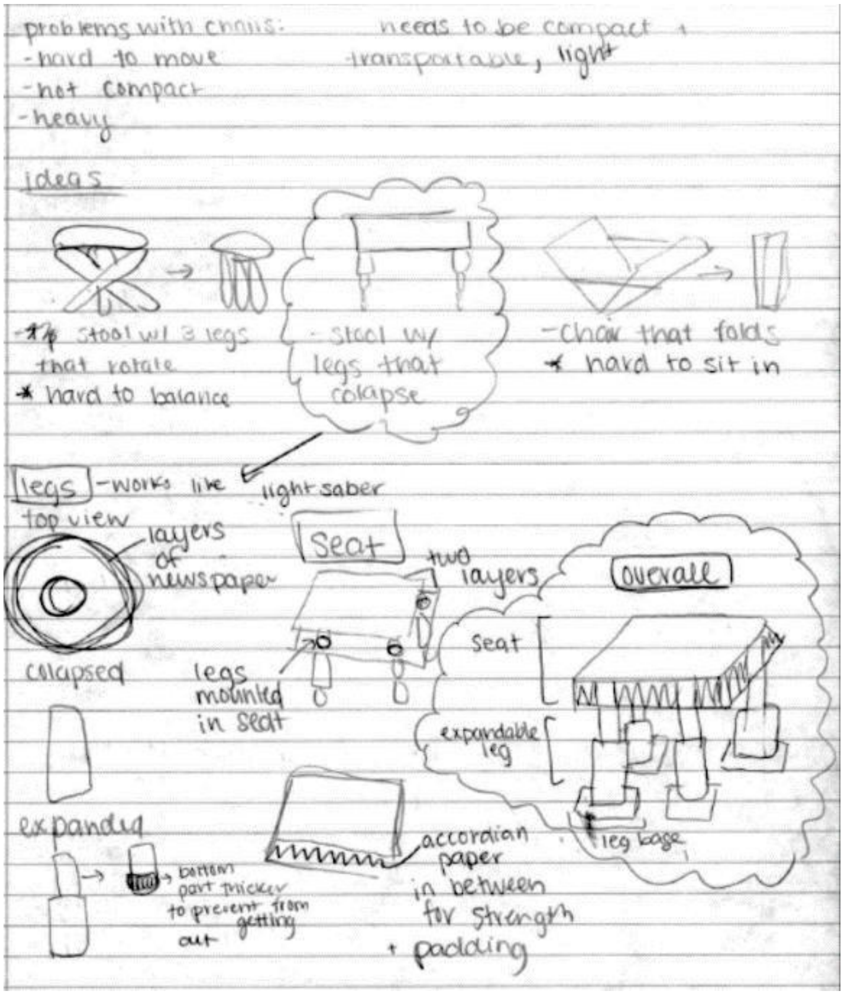


Figure 3. Chair Designed in Response to Design Prompt

In their reflections about what they learned in the first module, students identified learning how to approach a problem with creativity, design as part of a team, and persist through failures. As one student observed:

> I was not interested in even considering the possibility of creating something (I don't consider myself a creative type) until the class was given the task of identifying grand challenges that they would be interested in solving. Once this occurred, I realized how interested I would be in actually brainstorming potential solutions to the issues presented.

In the *Empathize* module, students: learned about engineering ethics; formed their design project teams; within those teams, created a short survey; then an interview protocol; interviewed students within their newly created team; and reflected on the interview process. To introduce engineering ethics, students read and responded to e-book case studies designed to provide first-year college students with initial insight into the profession of engineering, engineering ethics, and the social impact of engineering in society [25]. Students identified at least five real life cases with an ethical dimension (positive as well as negative) using examples from the e-book, and for each case, listed general ethical issues. They uploaded this assignment to the online course site and discussed it in a class session.

Students were then asked to form design teams, which occurred in the tenth class session. Often, students who had collaborated on the chair design activity described above reconvened to form a team. Other teams were formed by proximity (e.g., "We sat next to each other in class") or from prior relationships (e.g., "We kind of knew each other before the course started"). In all, 35 teams were formed; most ranged in size from four to six students. Ten teams were comprised entirely of engineering majors, while the remaining 25 teams included a mix of engineering students and students from other majors.

To introduce students to the need for engineers to interact with people to inspire human-centered innovation, the lead instructor presented material on how to design and implement a survey, and teams created a brief survey; the brief survey presented in the Appendix is an example of a team-designed survey. As a team, team members also created an interview protocol to learn about each other. Each student interviewed at least one other team member and reflected on how the interview had unfolded. Typical interview questions included, "What brought you to this university?"; "What activities are you involved in on and off campus?"; "What do you plan to major in and why?"; and "What are your long-term career goals?" Common interview reflections included, "I rushed through questions; I won't do that next time", "We should have had more open-ended questions to learn more about the person"; "I kept getting off track"; and "I should have asked more follow-up questions." These activities and reflections prepared them for tasks in the next design process module.

In the *Define* module, teams developed a problem statement to guide their design process. To do so, teams selected a Grand Challenge to address and researched what was known about that topic. For example, a team that selected solar energy researched the types of solar energy used in society, the impact of society and economics on solar energy, and solar energy pros and cons. Each team then interviewed at least three people outside of the class on their topic. Through their interviews, the solar energy team learned that: people have a general understanding of solar energy, most commonly gained through their knowledge of solar panels; profit can be made from solar energy, but initially it is expensive to start using solar energy; and solar energy use is good for the environment. Their resulting problem statement was: “There are problems with harnessing solar energy; thus, the number of people who know about solar energy is far smaller than it should be.” Each team uploaded a PowerPoint presentation to the online course site to describe their research resources and summarize what they learned to inform their resulting problem statement.

The *Ideate* module lasted seven class sessions. In this module, teams generated ideas to respond to their selected Grand Challenge, narrowed their ideas to one idea, and prepared a PowerPoint presentation to describe the process they undertook to select their one idea. To prepare students to engage in idea selection, the lead instructor described selection methods. He first described the multi-voting (red dot/green dot) method, highlighting that the method was useful to get an informal sense of team members’ ‘gut feelings’ about the different options. Teams then listed all ideas on a large sheet of paper and posted it on a wall. Each team member was given five green dots to identify five ideas they liked and five red dots to identify ideas they thought should be eliminated. This approach allowed teams to narrow ideas to a more feasible number.

The lead instructor then introduced the Decision Matrices and the Pugh Decision Matrix, in which teams created a matrix to compare ideas across design criteria. Teams scored concepts using both an equally weighted and weighed scoring system. Determining weights and assigning scores were highlighted as mechanisms that could be used to reach consensus. A class discussion was also focused on the use of weightings and some of its potential downfalls, such as reliance on a particular score and that it is acceptable to select concepts that did not have the highest weighted score. Students were free to use whatever methods of selection they liked but were required to reflect on the selection method used and to justify their selection decision.

As an example of the Pugh Method as used in our class, a team of six students (four engineering majors, two pre-med majors, all female) chose to address the challenge of providing access to clean water. Their problem statement was “The lack of clean water imposes health threats and impedes a normal lifestyle, contributing to the lack of access to education and propagating the cycle of poverty.” They researched the effects of lack of access to clean water worldwide and current techniques used to solve the water crisis (e.g., improving infrastructure such as pipes and canals, education to change consumption habits, harvesting rainwater, developing energy efficient desalination plants). They then brainstormed 20 ideas for providing access to clean water, narrowing down to 5 that seemed most feasible, and identified 10 design criteria. They then developed a weighted rating system, depicted in Table 2, for identifying which idea most fully met criteria, resulting in a decision to choose solar water disinfection.

Table 2. Example of Pugh Method Used to Select Idea

		Five Feasible Ideas				
Design Criteria	Weights (1-5)	Well	Recycle Waste Water	Water Filtration Systems	Drawing Water from Humidity	Solar Water Disinfection
Easy for Children to Use	3	+	-	-	-	+
Easy to Implement	4	-	+	-	+	+
Makes Water Clean	3	+	-	+	+	+
Makes Water Accessible	4	+	+	+	+	+
Inexpensive	4	+	+	-	+	+
Helps Many People	4	+	+	-	+	+
Reduces Water Pollution	4	+	+	+	+	+
Environmentally Friendly	4	+	+	+	+	+
Simple to Maintain	4	+	+	-	+	+
Can be Used Globally	3	+	+	+	+	+
Total Number of +		9	8	5	9	10
Total Number of -		1	2	5	1	0
Overall Score		8	6	0	8	10
Weighted total +		33	31	18	34	37
Weighted Total -		4	6	18	3	0
Overall Weighted Score		27	25	-1	31	37

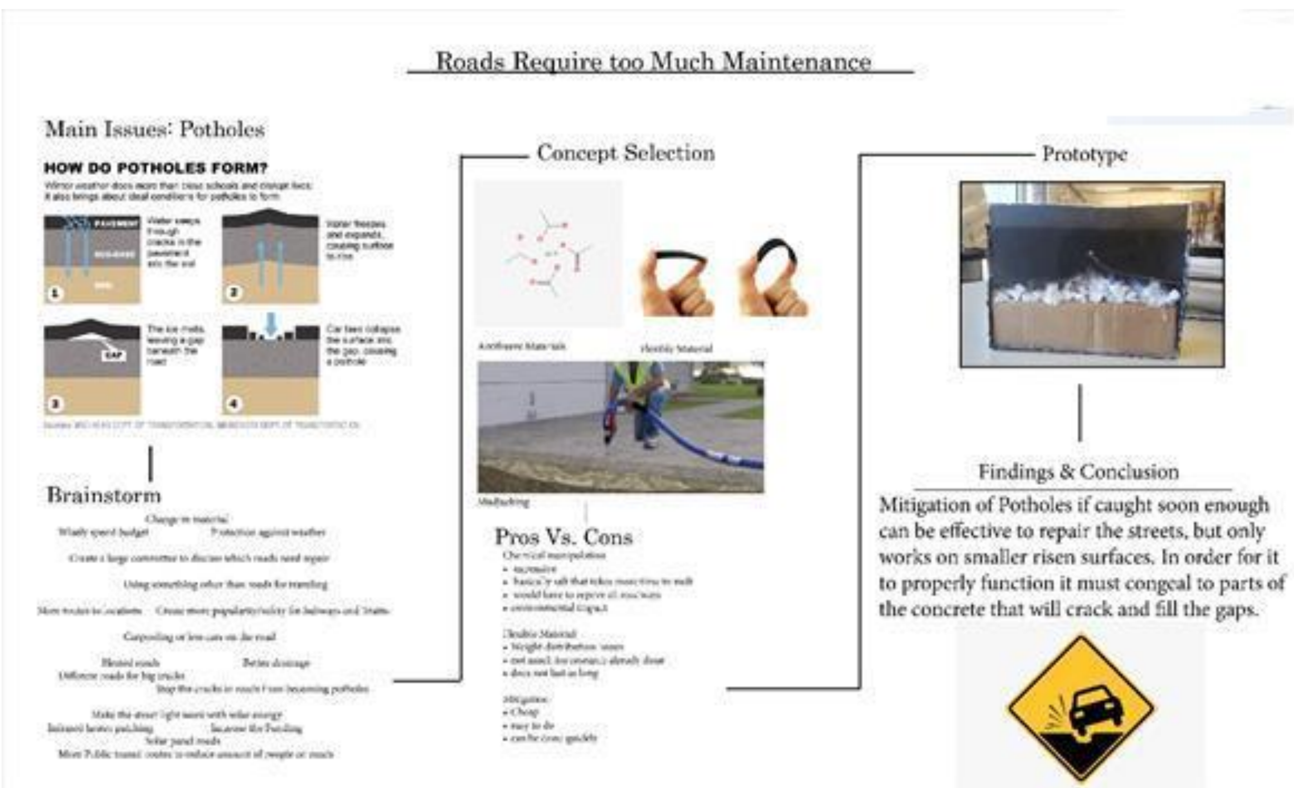
Solar water disinfection was the clear leader, and the team then designed a solar water disinfection system using tin foil, BPA free water bottles, and a collection barrel to collect rainwater, collect condensation, and disinfect the water bottles with one apparatus.

Each team created and uploaded a short presentation to the online learning site in which they listed the ideas they had generated and the process they used to narrow to one idea to pursue. In addition, the lead and support instructors met individually with each team during class to confirm that teams had completed this process and to discuss their experience with it. Teams reported that they found the selection process challenging but helpful, showing them the benefit of not selecting the first or easiest choice, and letting all team members have a say in the choice. Importantly to note, during these individual meeting with teams, instructors identified three instances in which teams were plagued by social loafing, a situation in which a person exerts less effort when working as part of a team than when working alone. The lead instructor addressed this by having candid (sometimes painful) conversations with team members and giving team members options to leave and form smaller teams.

The *Prototype* module began in the final six weeks of the course. Students were free to leave the large classroom to build and test their prototype. They also created a poster describing their design process experience from start to end. Teams presented their prototypes and posters on the last class day in a large auditorium. During these final weeks, the lead and support instructors met regularly with teams to assess their progress, answer questions, and provide guidance and support. Each of the 35 teams offered a final design that was an innovative response to a Grand Challenge. In Figures 4 – 6, we showcase team projects, accompanied by student reflections on what was learned through project participation. Although we recognize that the poster text is difficult to read, we provide these student artifacts to offer engineering instructors insight into how student teams displayed their engagement with the design process stages.

Figure 4. Team Project Addressing the Grand Challenge to Restore and Improve Urban Infrastructure

Roads Require Too Much Maintenance:
Fixing Potholes Using Alternative Paving

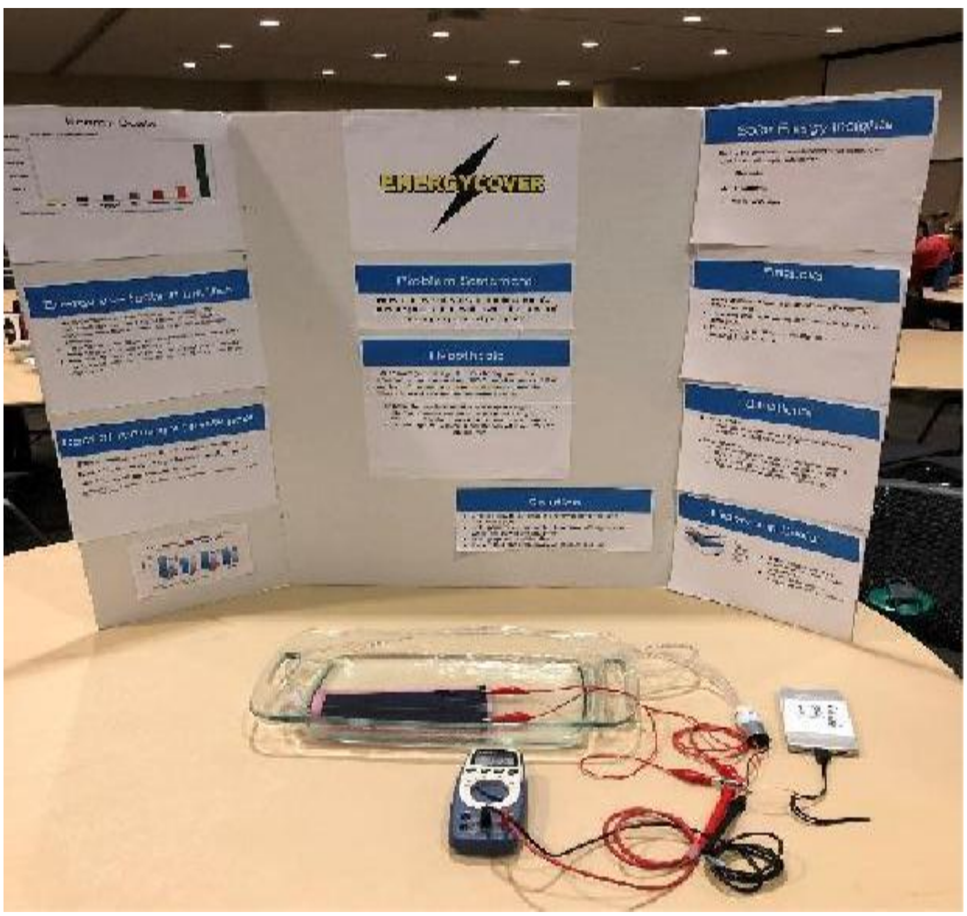


The project introduced important concepts relevant to the fields of engineering, including the engineering approach to solving problems, communications and computations, ethics, environmental responsibility and teamwork. Particular attention was paid towards how technology, engineering, and pervasive computing impact society. I will apply what I learned when I am working in a professional job and work in teams.

Because I want to be an engineer, the design process is extremely important for me because it is used so often. This project helped me with organization and scheduling. I had to create a schedule for when I wanted the prototype and presentation done. I got to be in a team and met some great people and the collaboration between us made our project great. I would not have thought of our idea by myself, but I also feel that the finished product wouldn't be the same if I wasn't in the team, which is a really unique relationship. This was the only class this semester where I worked in a team even though most engineering jobs are with other people and you are working together.

Figure 5. Team Project Addressing the Grand Challenge to Make Solar Energy Economical

Energy Cover: A Light, Collapsible Solar Panel Pool Cover That Can Be Easily Stored

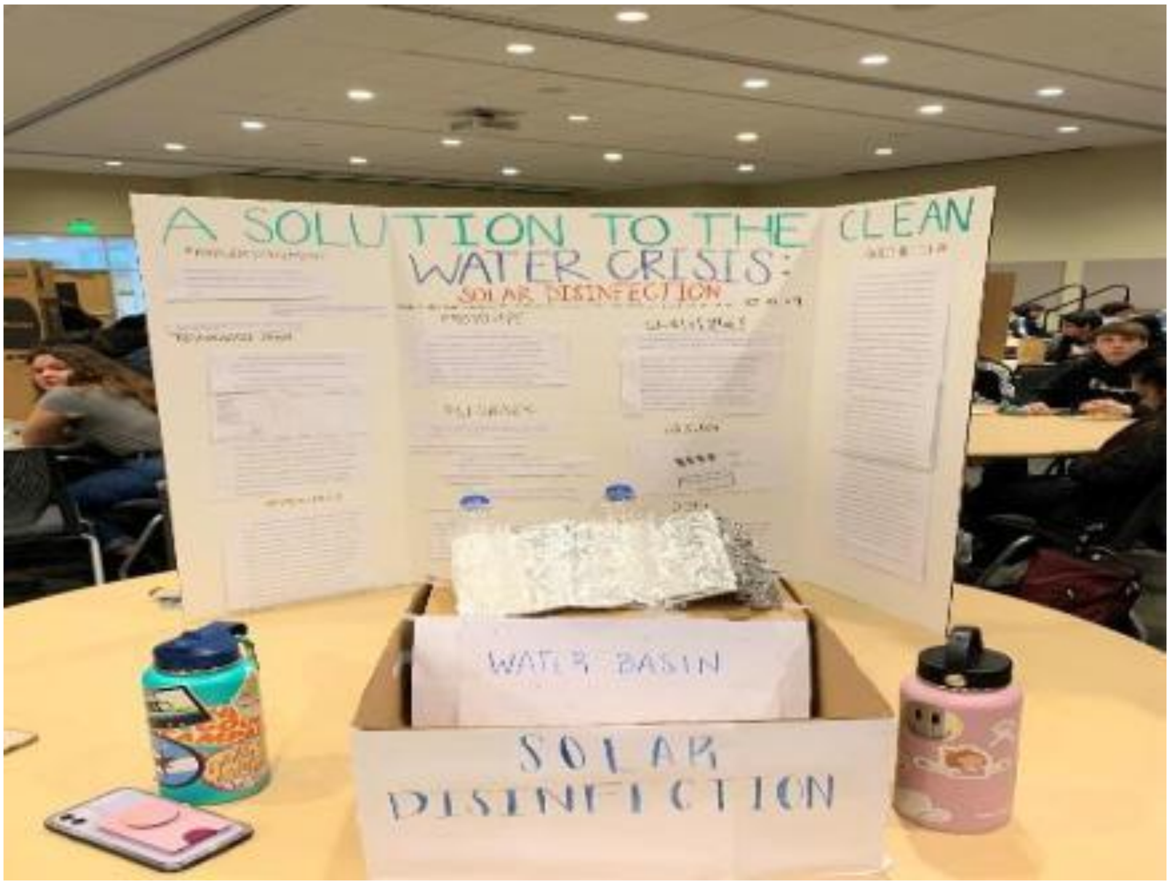


I learned many things from this project. The most important thing I learned is trust. Trust is very important to any field and if you don't trust someone then the team will fail. The second important thing I learned is that working in a team is better than working alone because you could find many solutions that you wouldn't by yourself. I will use these things in the future when it comes to my personal life and career because these things make a person successful.

I learned a lot from this project, like how to work in team. I learned how to identify the problem statement and how to solve it. I learned how to make a prototype by defining it first and then brainstorm the ideas with team members. I will use all the things that I have learned to make prototypes in the future.

Figure 6. Team Project Addressing the Grand Challenge to Provide Access to Clean Water

A Solution to the Clean Water Crisis: Solar Disinfection



This project provided insight into the field of engineering; while I previously imagined it to be a rigid topic, I learned that engineering requires a love for continuous learning, creativity, and resilience.

I learned how to investigate a problem and find viable solutions to it. I thought it was really cool to see how engineers use lots of public feedback to create their final idea. I enjoyed explaining our ideas to others and getting their feedback on it because it always left us with another problem to solve. There will always be problems to solve in the future and this taught me that others may have feedback about your problems and can help you figure it out. I definitely will use these skills in the future.

Conclusion

Our overarching purpose in this paper was to describe the use of the design process in an introductory engineering course that enrolled close to two hundred students, most of whom were in their first year in college. As we argued, these are the students who might most benefit from design process participation. We found that in general, the design process was transferable to this educational context. Most students seemed far more engaged than students in previous course offerings that had been delivered in a traditional format. Notably, students reported that in addition to learning course content, they learned creativity, persistence, problem-solving skills, leadership skills, and teamwork skills. However, perhaps the main contribution of engaging freshmen and other early-stage students in the design process was in fostering in them a greater understanding of the impact that engineers can have on society.

No study is without limitations, including this one. First, while our intention was to study the effect of design process participation on student problem solving confidence, growth mindset, and engineering identity, a technical glitch discovered too late limited our ability to definitively do so. However, student artifacts and comments strongly suggest that most students likely saw substantial gains in these outcomes. Second, while our intention was not to follow students beyond this course offering, a longitudinal approach in which we did so may reveal potential long-term effects of integrating the design process early in engineering education. Third, the campus upheaval caused by the Covid-19 situation limited our ability to obtain previous data allowing us to compare how student cognitive gains, engagement, and retention in the fall 2019 course compared to those in earlier course offerings. However, a comparison study was not our original intent, although we acknowledge it would have made our study results more robust. Further, we recognize that our modified use of the design process in this course did not constitute a full immersion in the process as has been described elsewhere [13]–[15]. No students traveled to other countries to engage with external stakeholders, and no design project was continued beyond course conclusion. However, the design process was successfully implemented in this introductory course and gave students, most of whom were in their first year of college, a strong foundation upon which to build their professional development. We hope that future researchers in this area make note of these limitations and find within them avenues for future research.

We end by suggesting that our work scales to a wider audience of engineering instructors who might use this work to self-reflect on how the integration of the design process in their own courses, especially in those enrolling students in their first year of college, might encourage student engagement and strengthen student engineering identities. We acknowledge that challenges come with the decision to implement the design process, including the possibility of social loafing and instructor discomfort that might arise from implementing group-based (as opposed to individual) evaluations of student performance. The transition from teacher-centered to learner-centered instruction often involves a consideration of challenges such as these. However, our experience in integrating the design process in this early-stage engineering class leads us to believe that ultimately, the goal of setting emerging engineers on their path to educational and professional success was achieved.

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Appendix: Example of Team-developed Survey for Homeowners Without Solar Power

1. What is your opinion of solar power?

- Very low
- Low
- No strong opinion
- High
- Very high

2. Does the option of using solar power for your house seem viable for you at this time?

- Very much no
- No
- "Maybe" or "I don't know"
- Yes
- Very much yes

3. What is keeping you from using solar power for your house? Please select all that apply.

- [ ] Cost
- [ ] Time commitment
- [ ] Inconvenience/hassle
- [ ] Incompatibility of house (known for sure)
- [ ] Incompatibility of house (not quite confirmed)
- [ ] Aesthetic concerns
- [ ] My HOA
- [ ] Preference of other person (e.g., partner) to not use solar power
- [ ] Other